Hard QCD

Daniel Maître

CERN/IPPP

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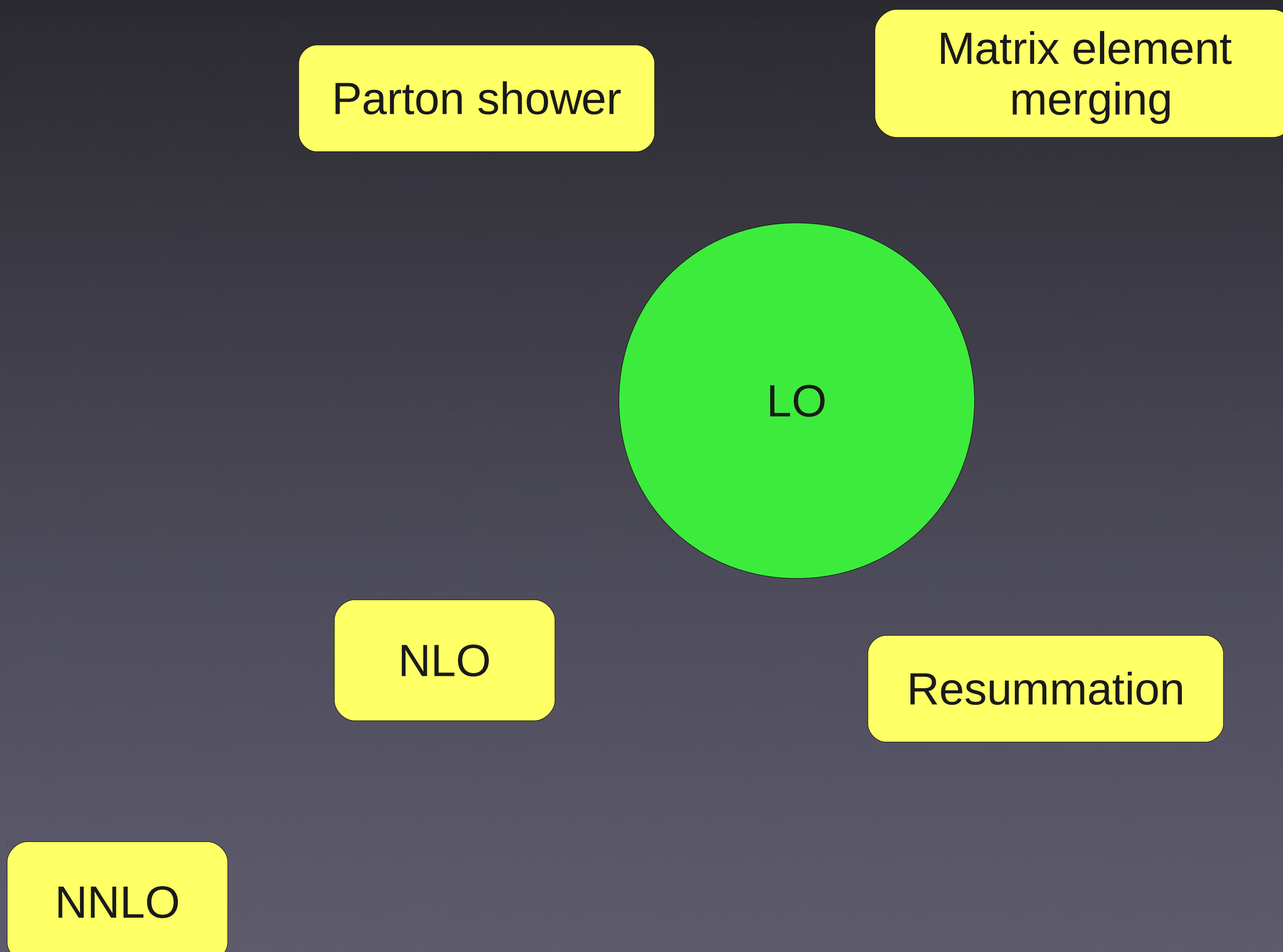
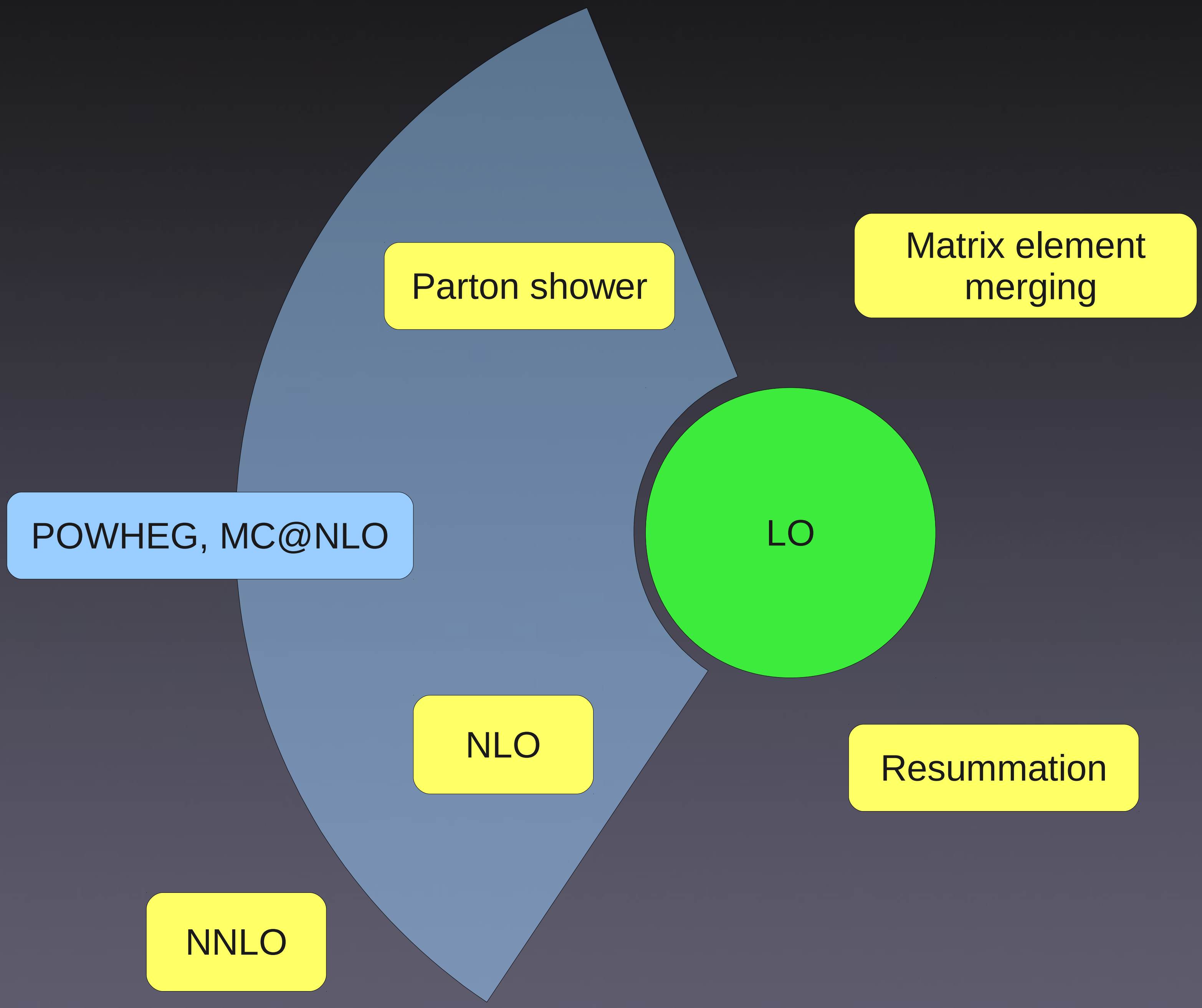
Outline

- Progress in high multiplicity NLO calculations
- Quick LO aside: W polarisation
- NNLO

Beyond LO


Parton shower
Matrix element merging
LO
NLO
Resummation
NNLO

Beyond LO



Parton shower
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POWHEG, MC@NLO
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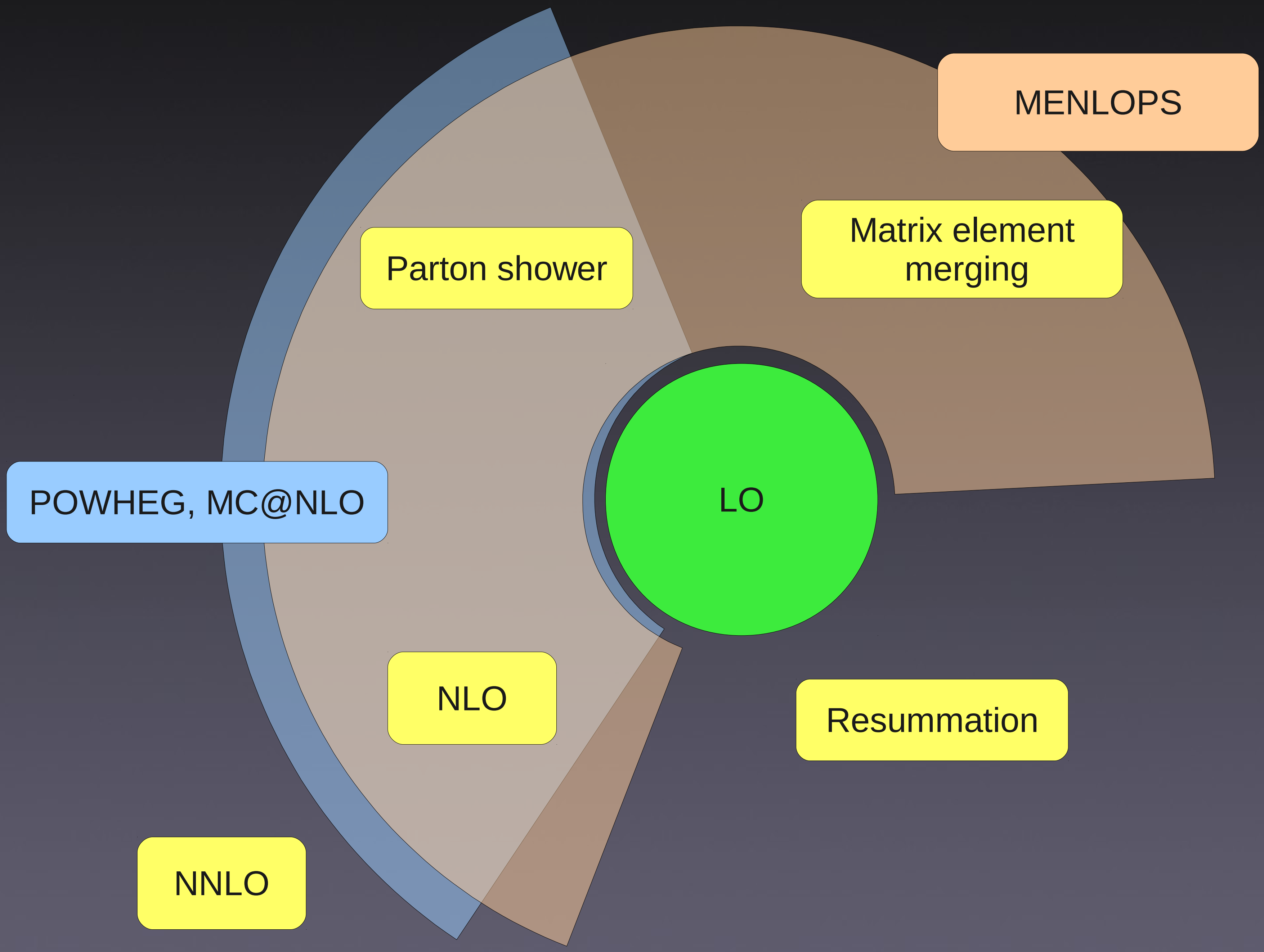
MENLOPS
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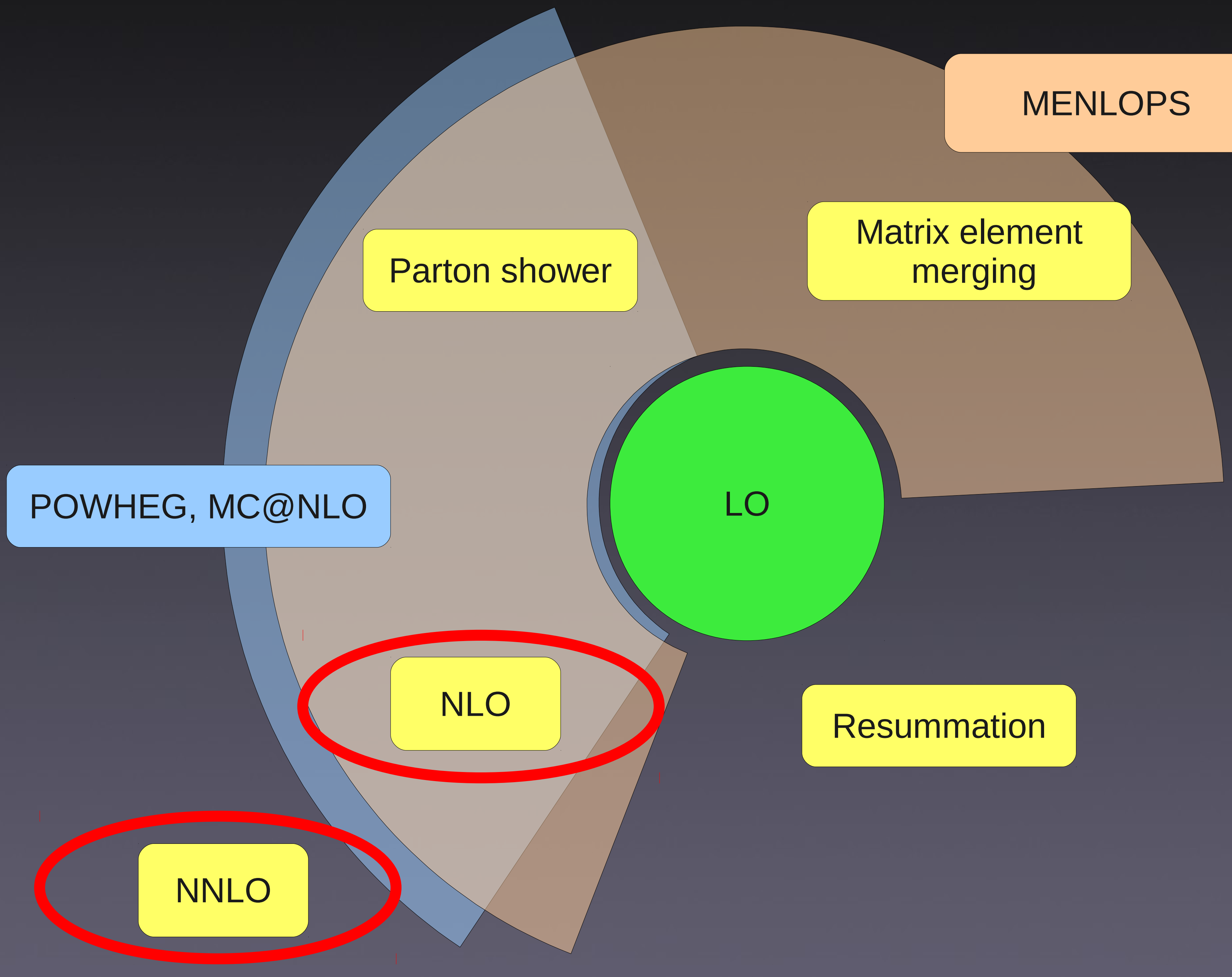
MENLOPS
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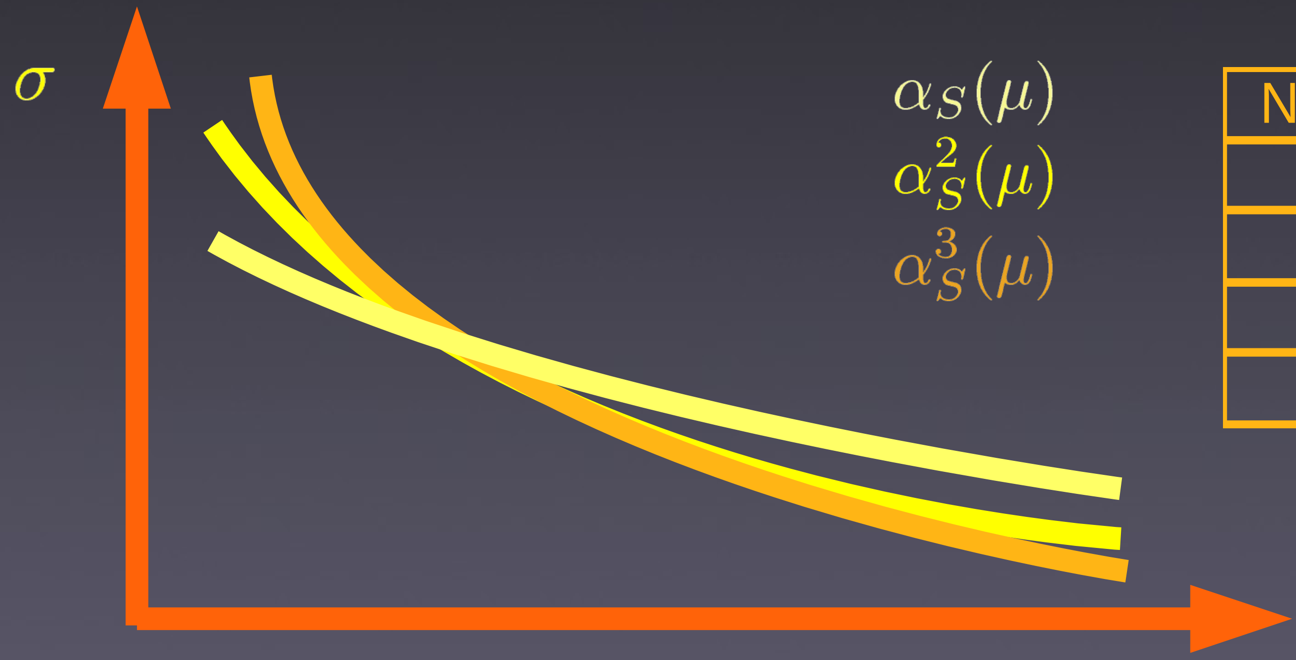
NLO Calculations

- Increased precision compared to LO
  - Absolute normalisation
  - Better shape of observables
    → more confidence in extrapolating background to signal region
  - Reduced factorisation and renormalisation scale dependence

Renormalisation scale dependence

- Scale dependence increases with number of jets

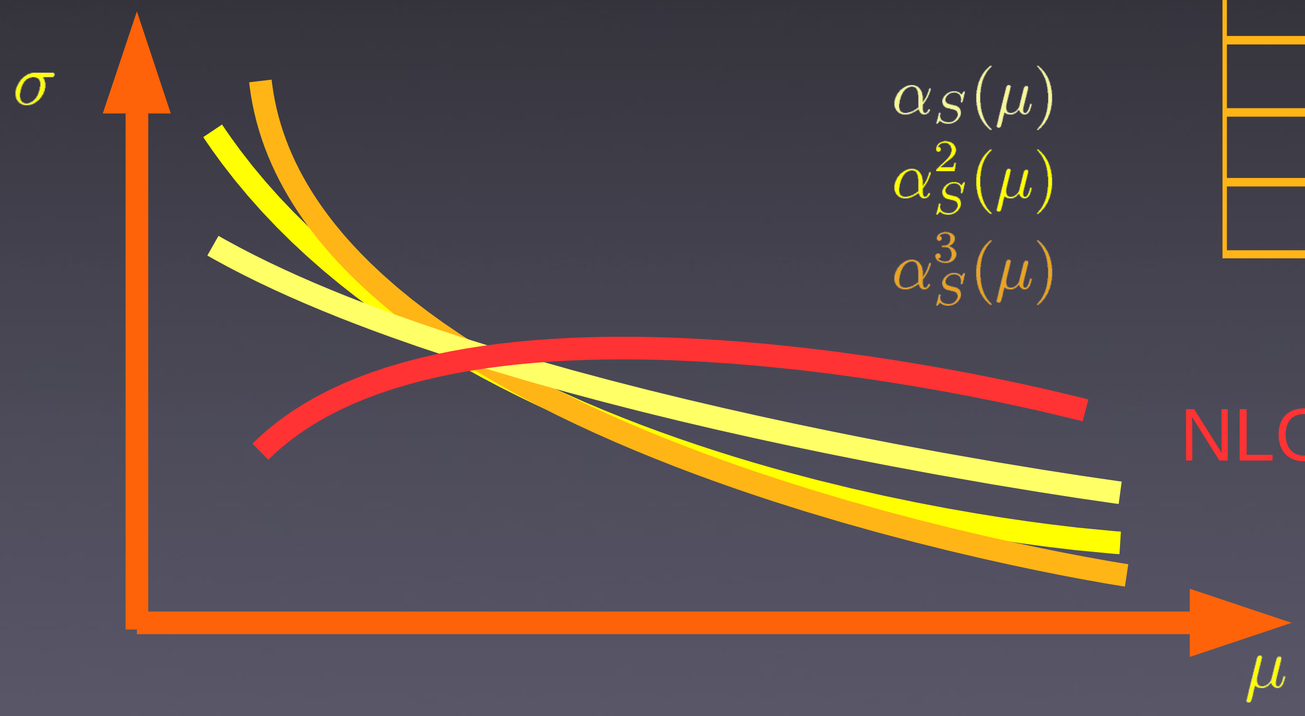


Number of jets	LO
1	9%
2	28%
3	47%
4	64%

[from table I in arXiv:1009.2338]

Renormalisation scale dependence

- Scale dependence increases with number of jets



Number of jets	LO	NLO
1	9%	4.5%
2	28%	5.2%
3	47%	7.8%
4	64%	8.4%

[from table I in arXiv:1009.2338]

Theory prediction

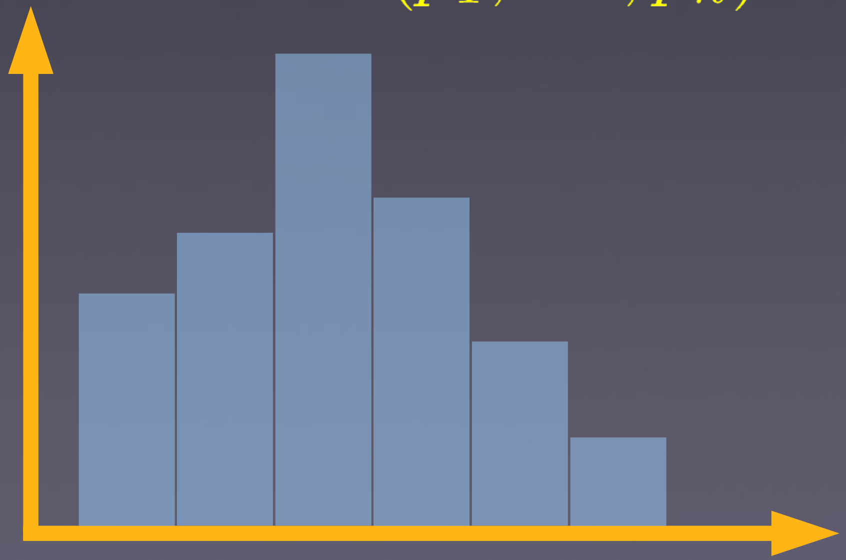
- Generate a phase-space configuration with n final state particles

$p_1, \ldots, p_n$

- Compute value of the observable and weight

$O(p_1, \ldots, p_n)$ $W(p_1, \ldots, p_n)$

- Bin

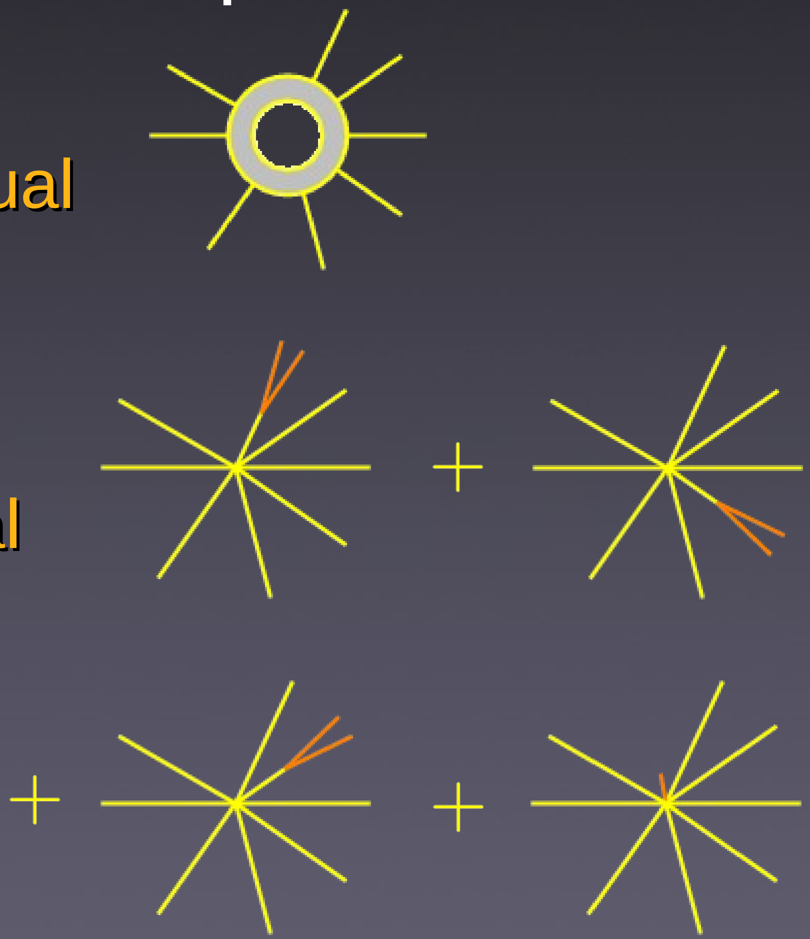


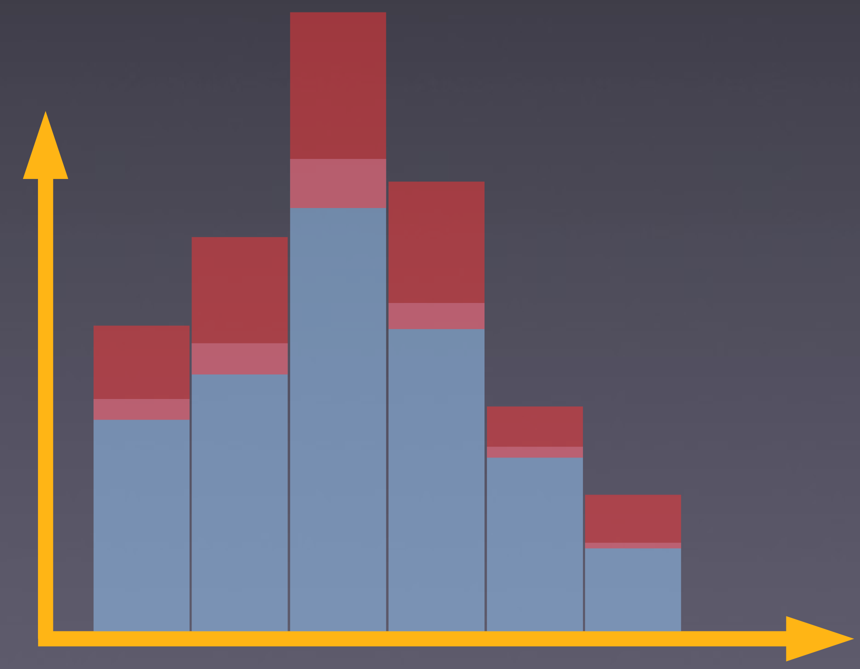
NLO Corrections

Consider (infrared safe) observable and add contributions that have an higher order in perturbation theory

Virtual

Real





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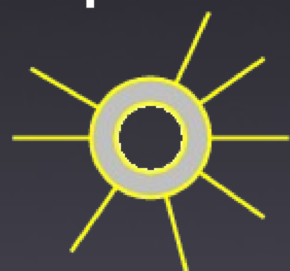
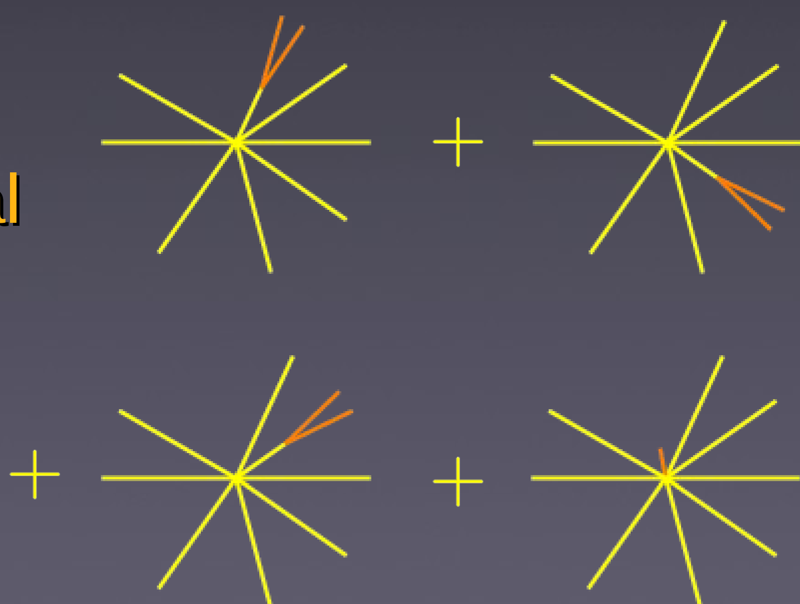


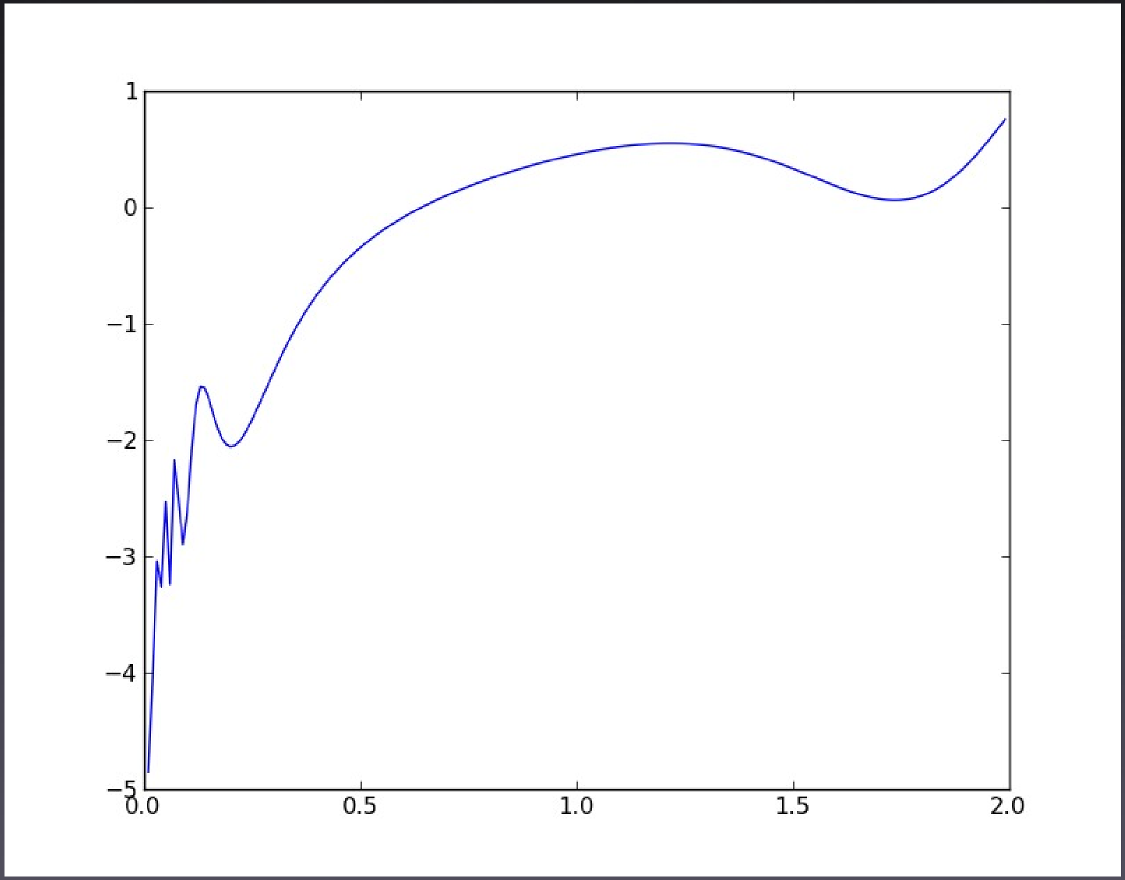
Has explicit divergences coming from integration over the loop momentum

Real



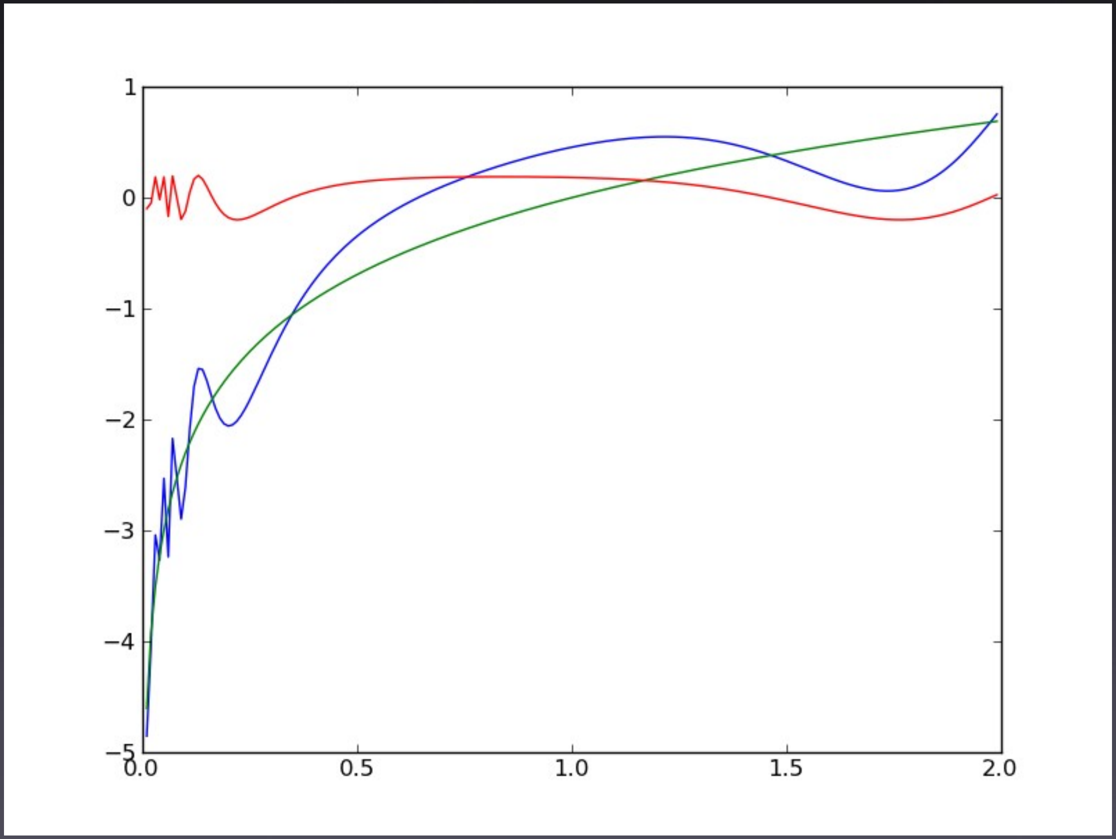
Has divergences when integrating over soft and collinear phase space

Subtraction method



- Need to integrate complicated function
- Function is divergent: need a regulator

Subtraction method



- Find a simpler function that captures the singular behaviour
- Integrate it analytically
- Integrate the difference numerically

$$\int f(x)dx = \int \tilde{f}(x)dx + \int \left(f(x) - \tilde{f}(x)\right) dx$$

$$= \mathcal{D}^{\text{ana}} + \mathcal{F}^{\text{ana}} + \mathcal{F}^{\text{num}}$$

Subtraction method

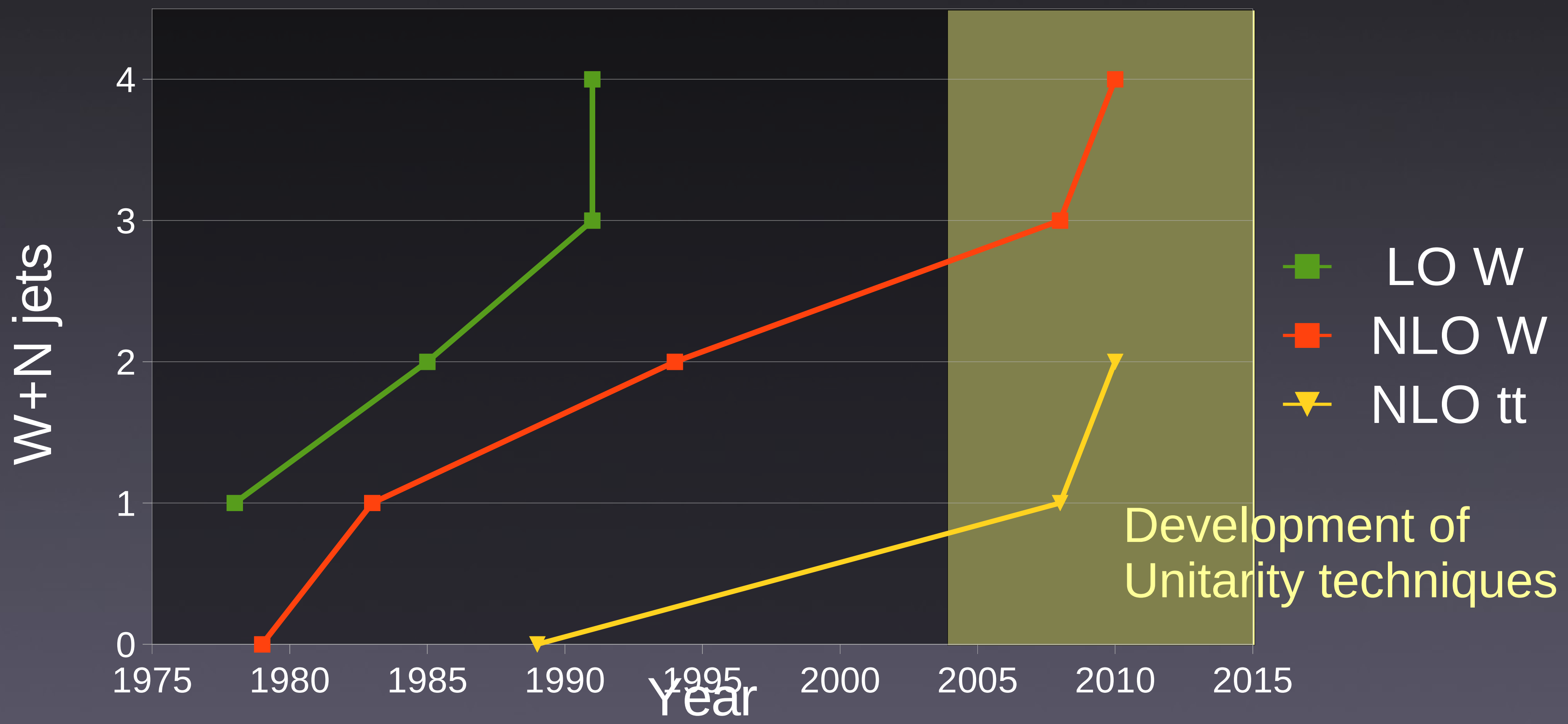
- Two tasks :
  - Construct approximation
  - Integrate them analytically
- “Solved” for NLO
  - Catani-Seymour
  - Frixione-Kunszt-Signer
  - Antenna functions
  - Many public implementations
- Work in progress at NNLO

A lot of progress in NLO QCD computations

- Many groups working on NLO corrections
- New frontier 2 -> 4 to 2->5
- Many progress towards automation

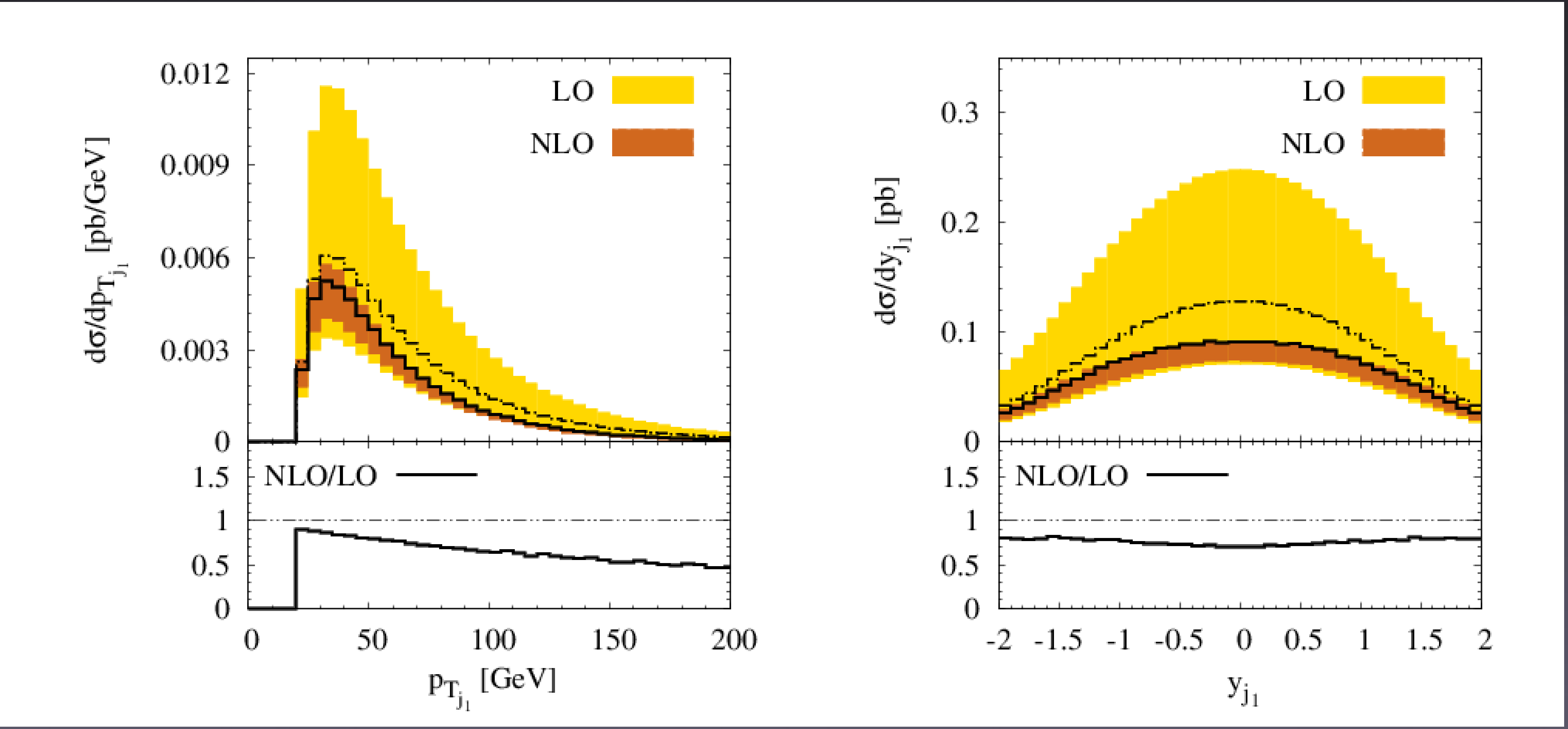
Progress

- W/top pair +jets NLO cross section



Top pair + 2 jets

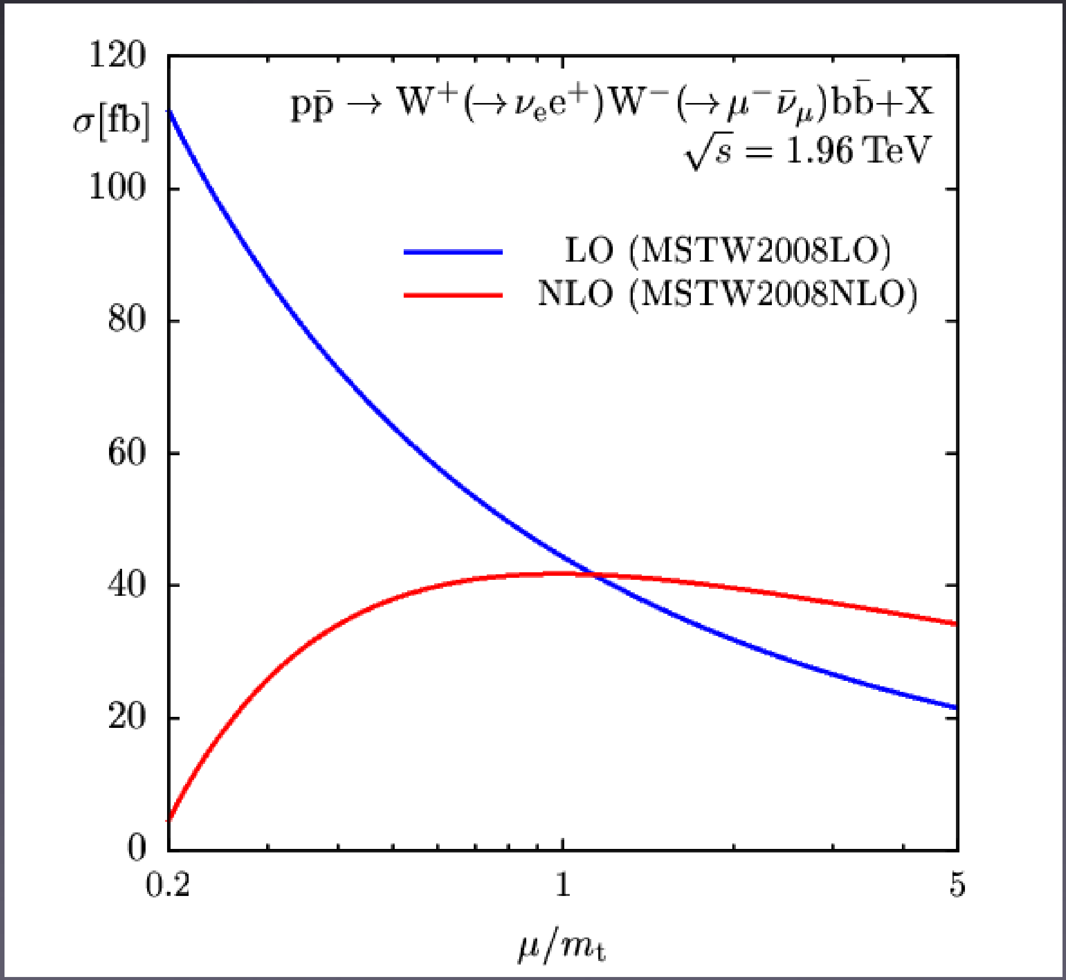
Bevilacqua,Czakon,Papadopoulos, Worek
[ArXiv:1108.2851]



$\mu = m_t$

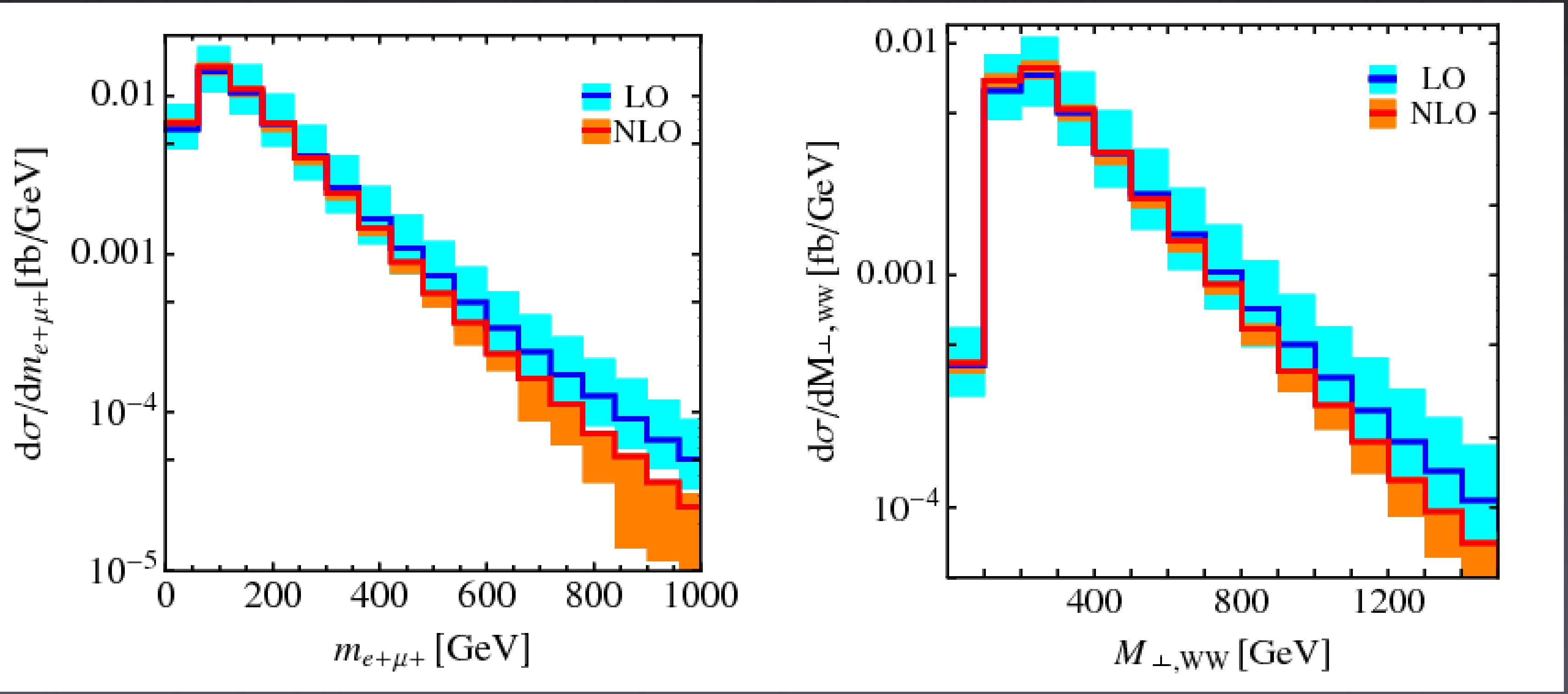
$W^+W^-b\bar{b}$

Denner, Dittmaier, Kallweit, Pozzorini
[ArXiv:1012.3975]



W^+W^+jj

Melia, Melnikov, Röntsch, Zanderighi
[ArXiv:1007.5313]



$\mu = 150\,\mathrm{GeV}$ Scale variation $50\,\mathrm{GeV} < \mu < 400\,\mathrm{GeV}$

In POWHEG BOX: Melia, Nason, Rontsch, Zanderighi [arXiv:1102.4846]

2 → 5 processes

- e+e → 5 jets
  Frederix, Frixione, Melnikov, Zanderighi
  [ArXiv:1008.5313]
- W+4 jets
  [Berger,Bern,Dixon,Febres Cordero,Forde,Gleisberg,Ita,Kosower,DM]
  [ArXiv:1009.2338]
- Z+4 jets

  [Ita,Bern,Dixon,Febres Cordero,Kosower,DM]
  [ArXiv:1108.2229]

Challenges

- Conceptual challenges
  - Uncertainties estimation
    - Scale and PDF variation
- Technical challenges
  - NLO computations are CPU expensive
  - Automation
  - Numerical accuracy of virtual part
  - Phase-space integration
- Technical and conceptual challenge
  - Merge NLO samples with different multiplicities

Prospects

- Rapid progress for NLO computations
  - Automation of virtual matrix elements computation
  - Improvement of the efficiency of real part
  - Combination with Parton shower
    - Herwig++
    - (a)MC@NLO
    - POWHEG Box
    - Sherpa
    - ...

W polarisation @ LHC

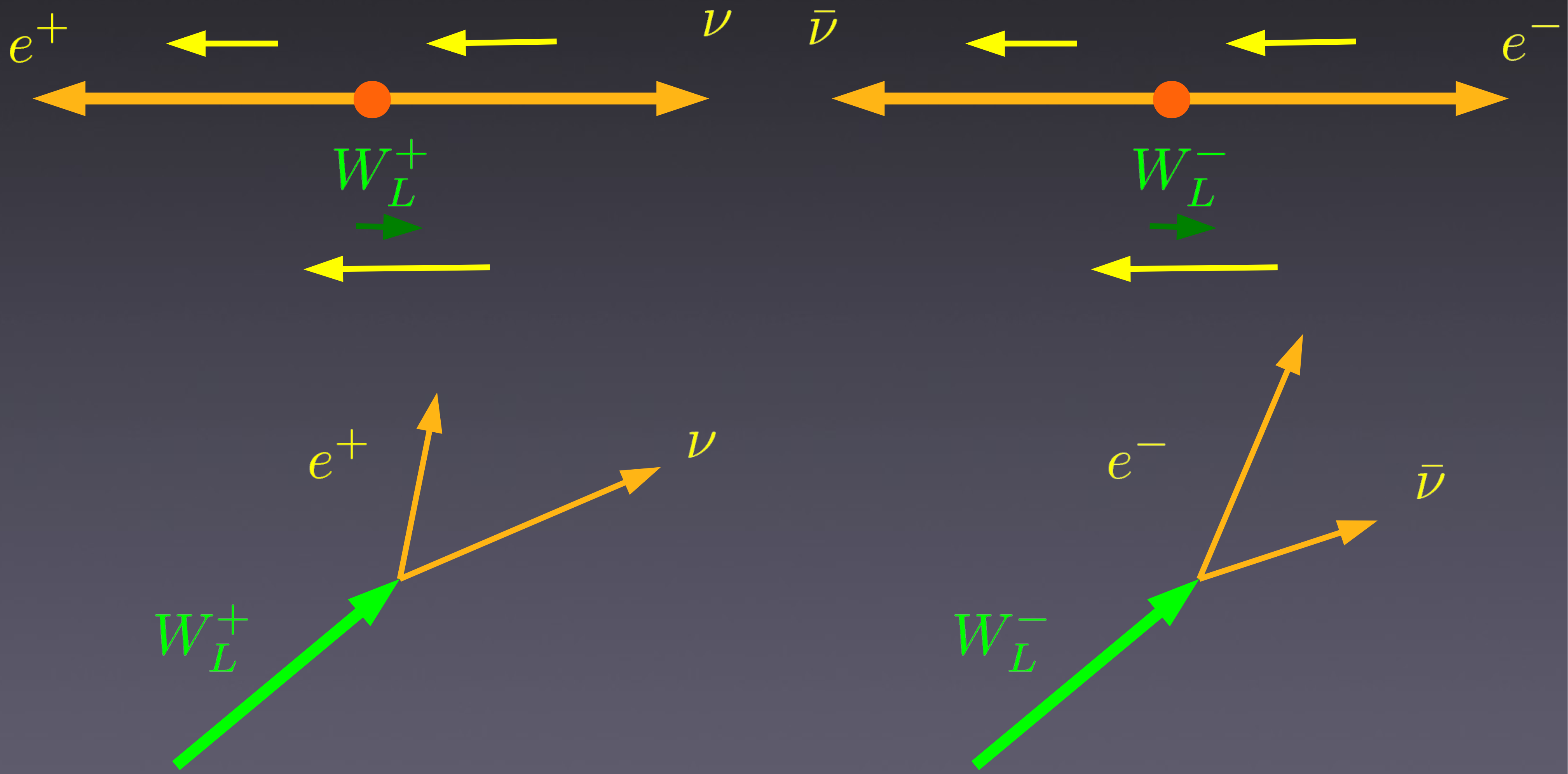
W polarisation @ LHC

[arXiv:1103.5445]

- Large transverse momentum W bosons the LHC are predominantly left-handed at the LHC (not the same as low *W* pT polarisation)
- Can be used to distinguish prompt W+jets from Ws produced in top pair decay, Higgs production or NP.
- Polarisation fractions are quite robust with respect to radiative corrections.

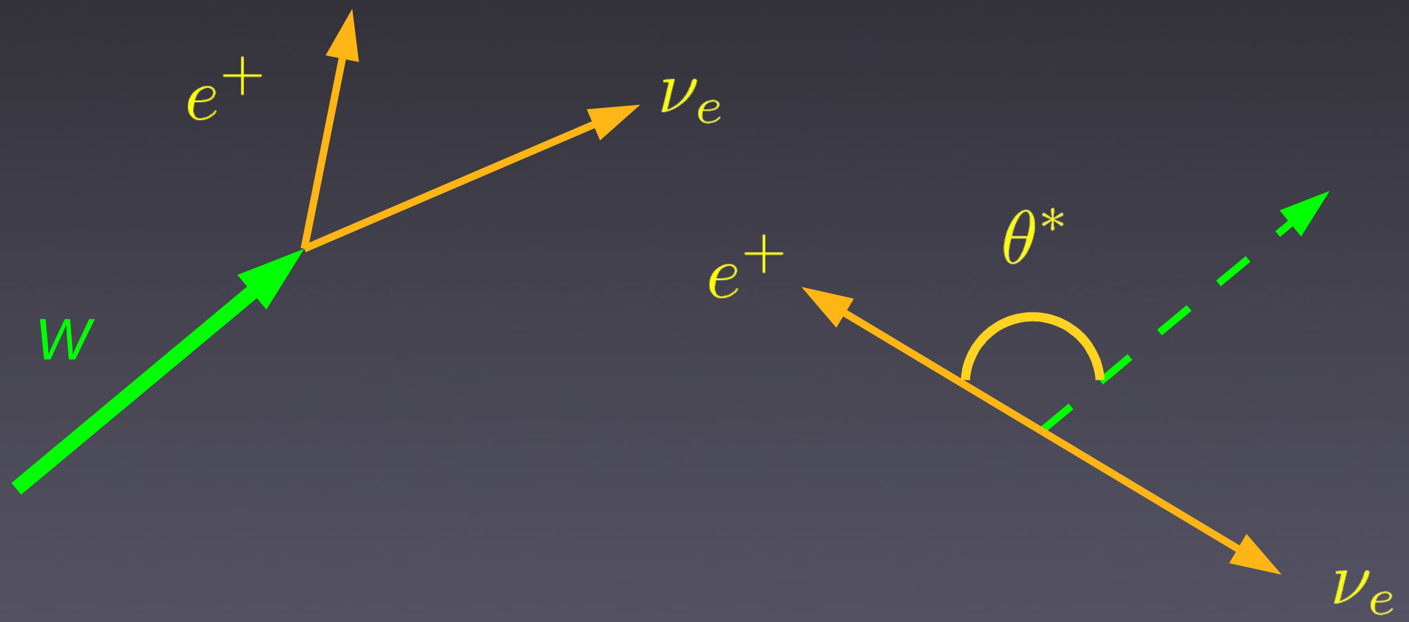
Left polarised *W*s

- Polarisation in the W flight direction



W decay in W rest frame

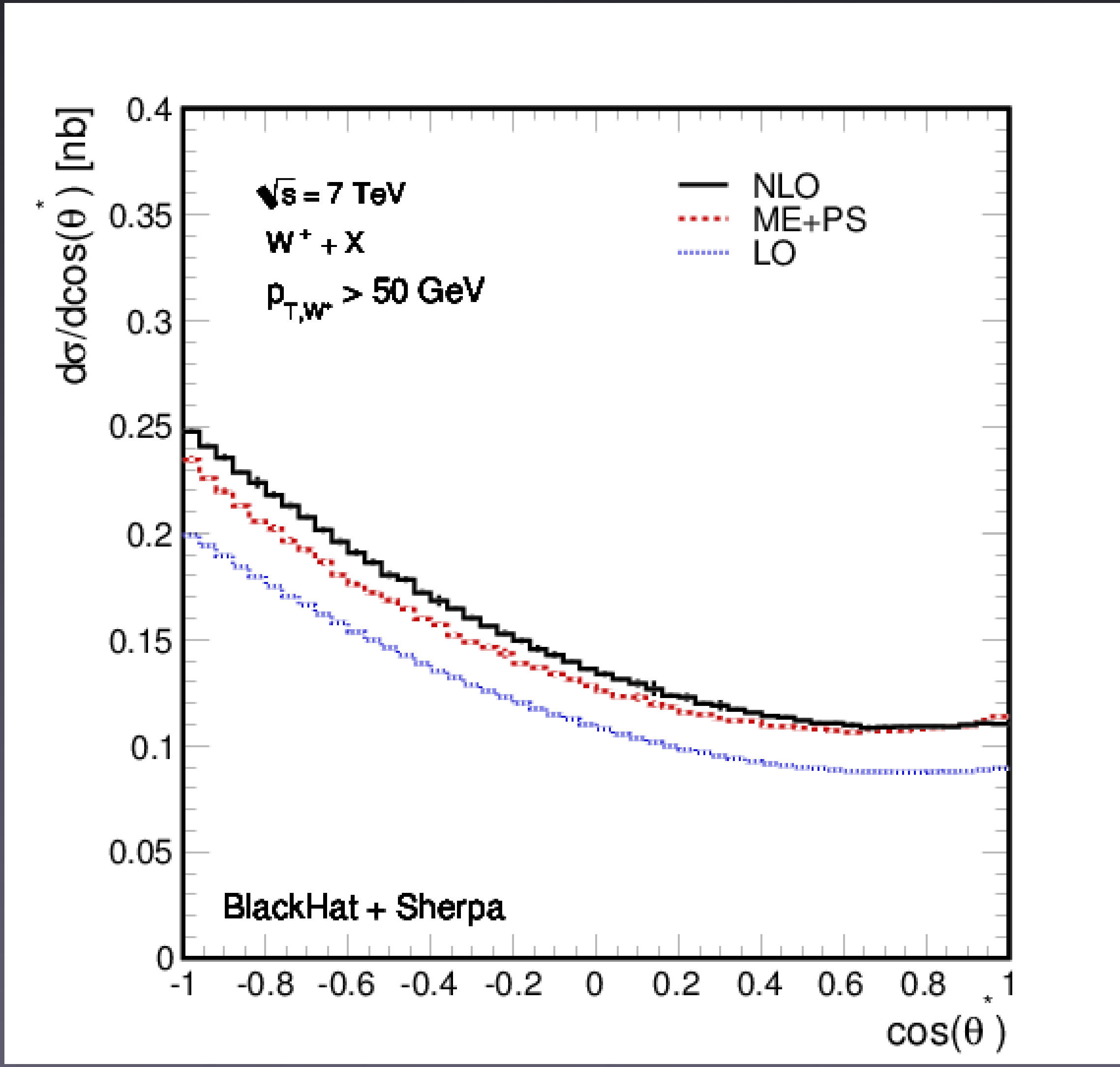
- Define θ^* as the angle of the charged lepton wrt the *W* flight direction in the *W* rest frame



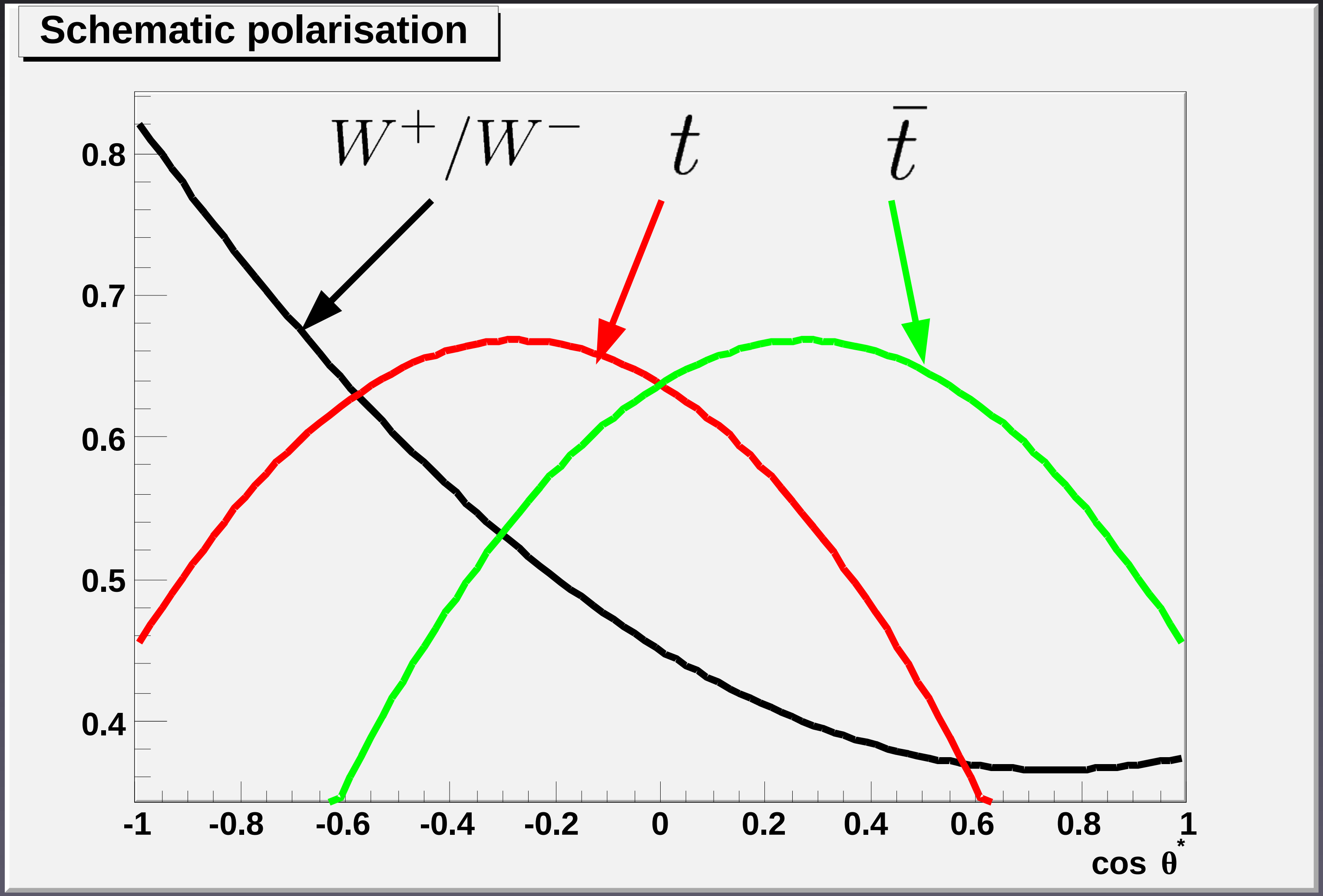
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 f_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 f_R + \frac{3}{4}\sin^2\theta^* f_0$$

Cos Theta* distribution

- Left polarisation clearly visible



W polarisation



NNLO 2 --> 2

- $pp \to Vj$
  - Crossing of $e^+e^- \to 3j$
- $pp \to jj$
- $pp \to t\bar{t}$

NNLO dijet production

[Gehrmann-De Ridder, Gehrmann, Glover, Pires]

- Do “gluons only” in a leading colour approximation as a proof of concept
  - Two loop virtual matrix elements know
  - Almost all the 1-loop 5 gluons matrix elements
  - Some “initial-initial”subtraction terms need to be integrated

NNLO top pair production

- Last missing ingredients are coming into place
  - Double real radiation [Czakon] [ArXiv:1101.0642]
  - Soft limit of one-loop amplitude with massive quarks [Bierenbaum,Czakon,Mitov] [ArXiv:1107.4384]
- No program puts all the pieces together as of now

Conclusions

- NLO
    - predictions are becoming available for many high multiplicity processes
    - Automation is underway
    - New frontier 2 → 5
- NNLO
    - *pp* -> *Vj* and *jj* and $t\bar{t}$ underway
- There are still effects to be discovered